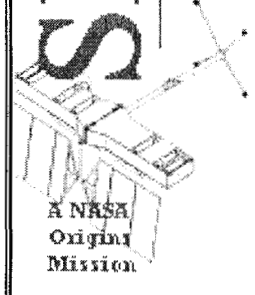
JPL

Space Interferometry Mission

SIM



Science Opportunities with the Space Interferometry Mission

IAU Colloquium 180, Washington, D.C.

Rudolf Danner
Jet Propulsion Laboratory
California Institute of Technology

March 29th, 2000

Key Science Objectives

Demonstrate Technology of Synthesis Imaging

Indirect Planet Detection Down to a Few Earth Masses (goal: 1 μas; min: 3 μas)

Technology

Science *

Demonstrate Technology of Starlight Nulling

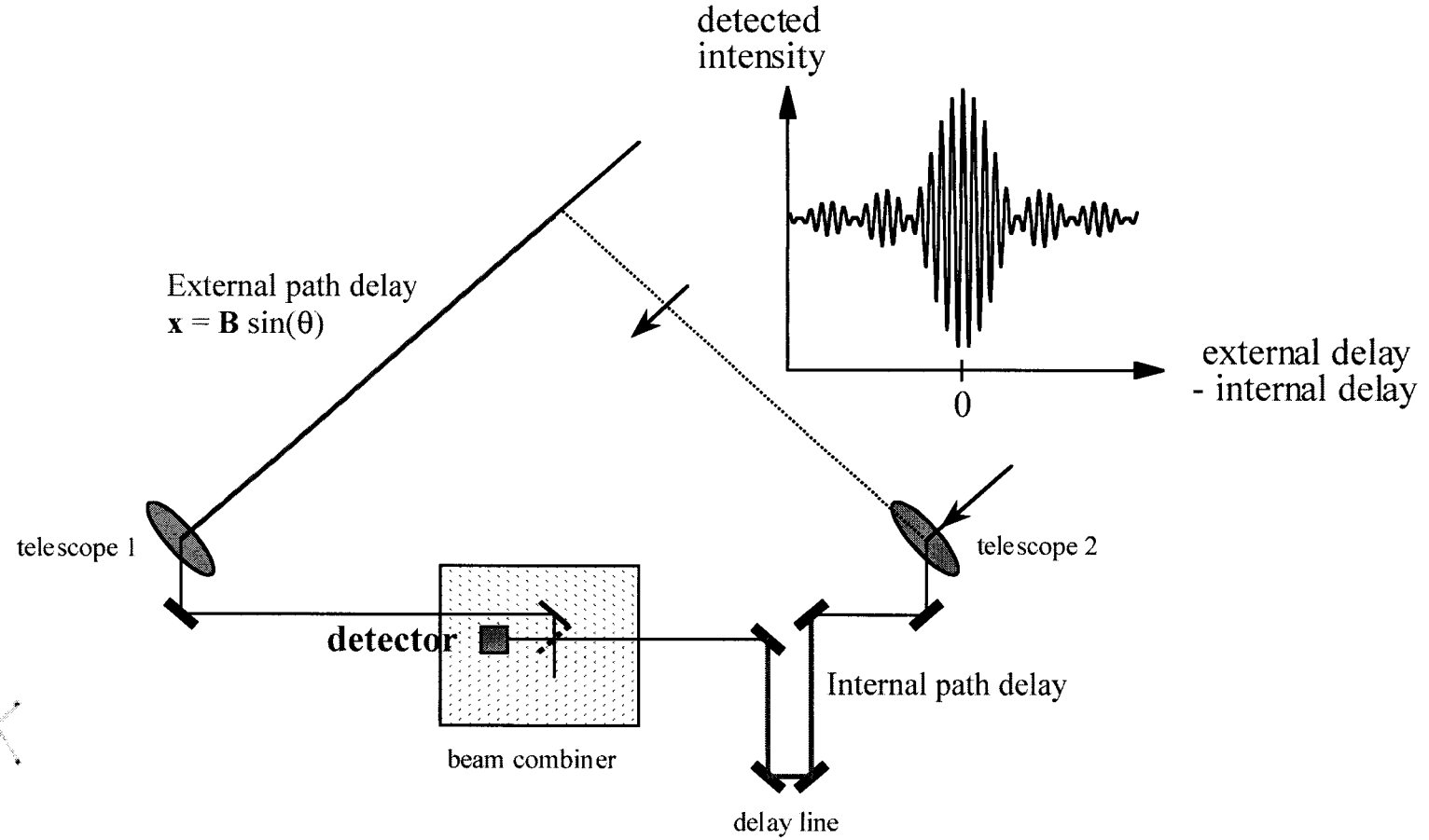
Ultra Precision Global Astrometry (goal: 4 μas; min: better than 3 0μas)

Usher in the Era of

Long Baseline, Short Wavelength Interferometry for Astrophysical Observation

* Technology maturation over the next few years will determine the ultimate achievable performance

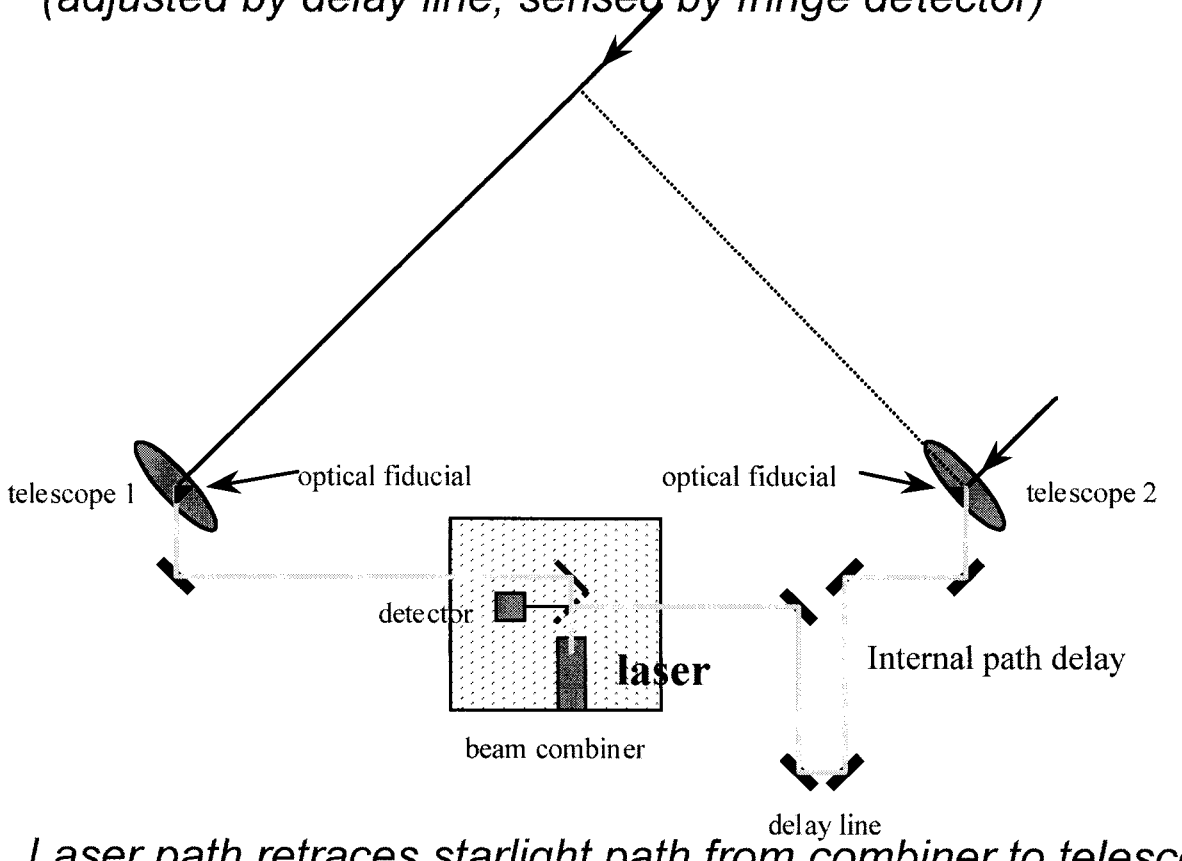
SIM Astrometric Measurement



The peak of the interference pattern occurs when the internal path delay equals the external path delay

Internal Metrology

Laser gauge measures internal delay
(adjusted by delay line, sensed by fringe detector)



Laser path retraces starlight path from combiner to telescopes

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External Metrology

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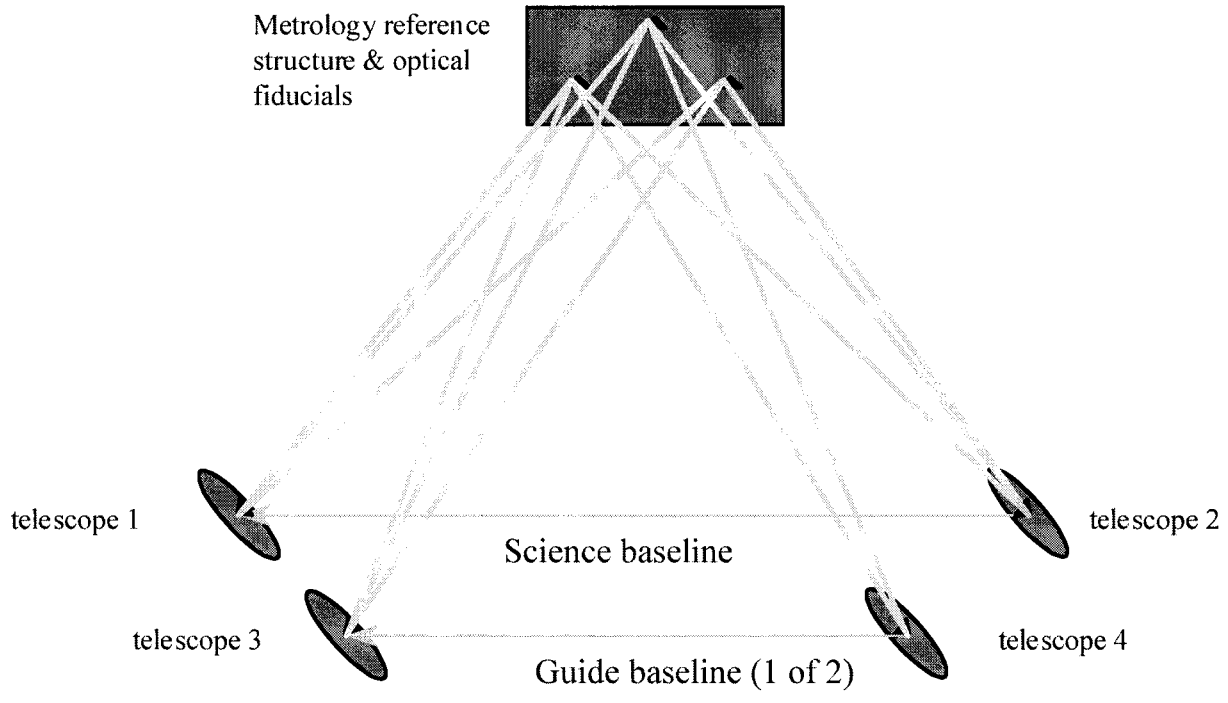
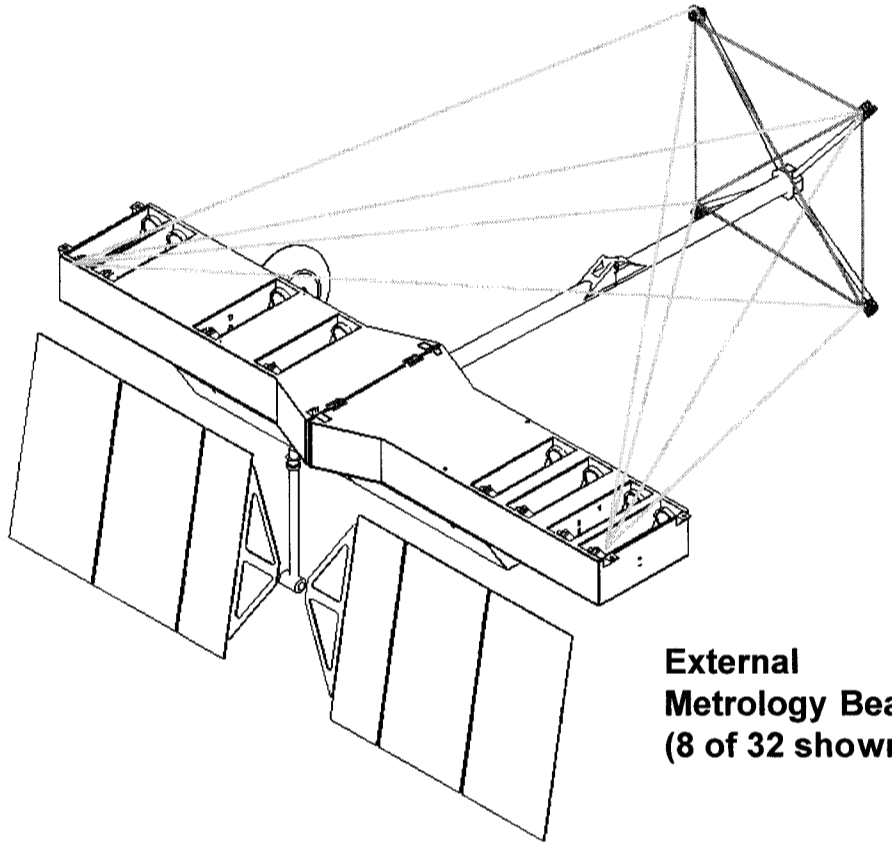


The attitude information is used to stabilize the science interferometer by commanding its optical delay line

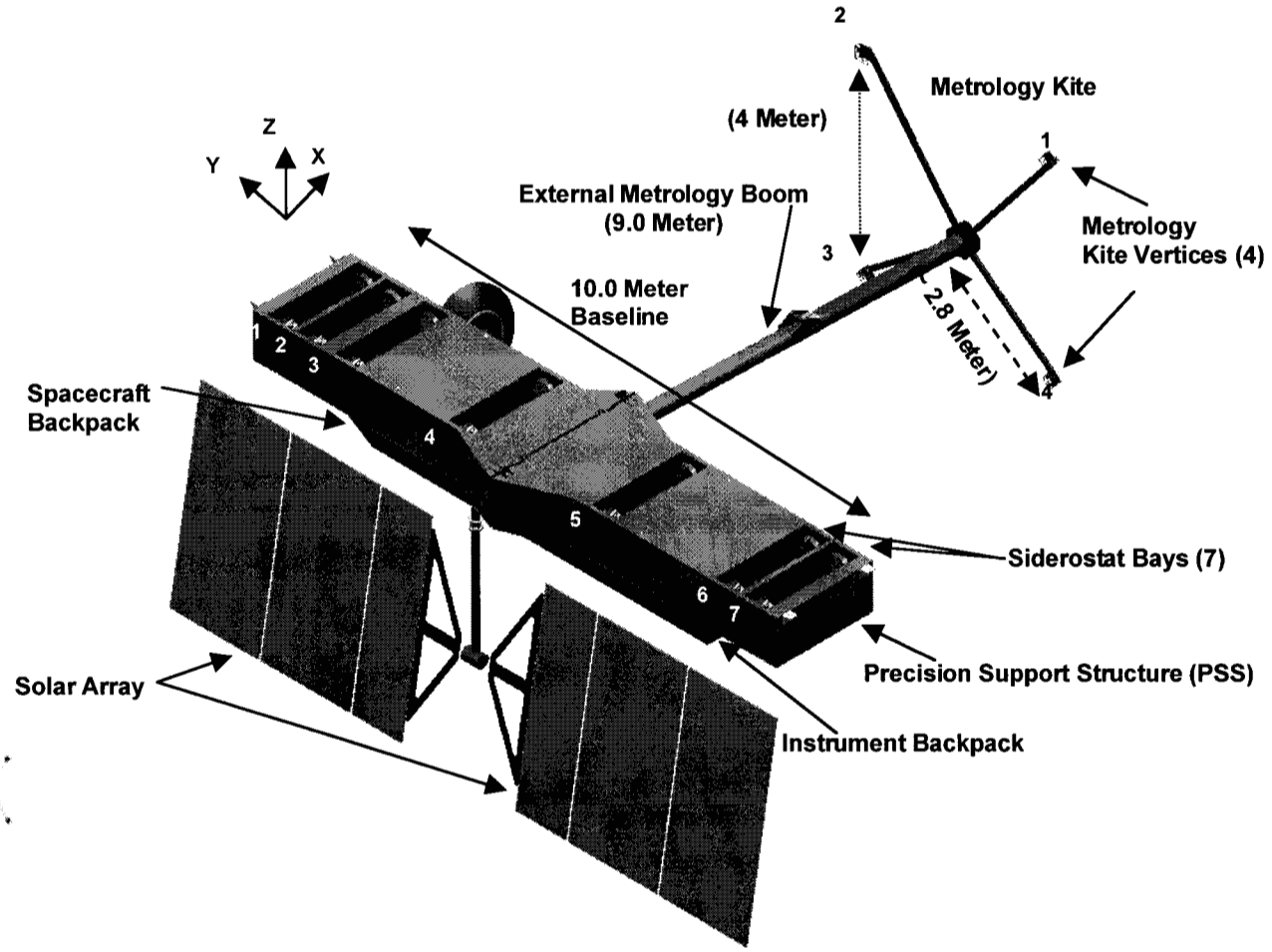
External Metrology



External Metrology Beams (8 of 32 shown)

- Measures relative orientation of science and guide baselines
- Allows accurate transfer of attitude information from guides to science interferometer
  - Science interferometer stabilized by commanding its delay line
  - Provides long integration time for faint stars

SIM Flight System Configuration



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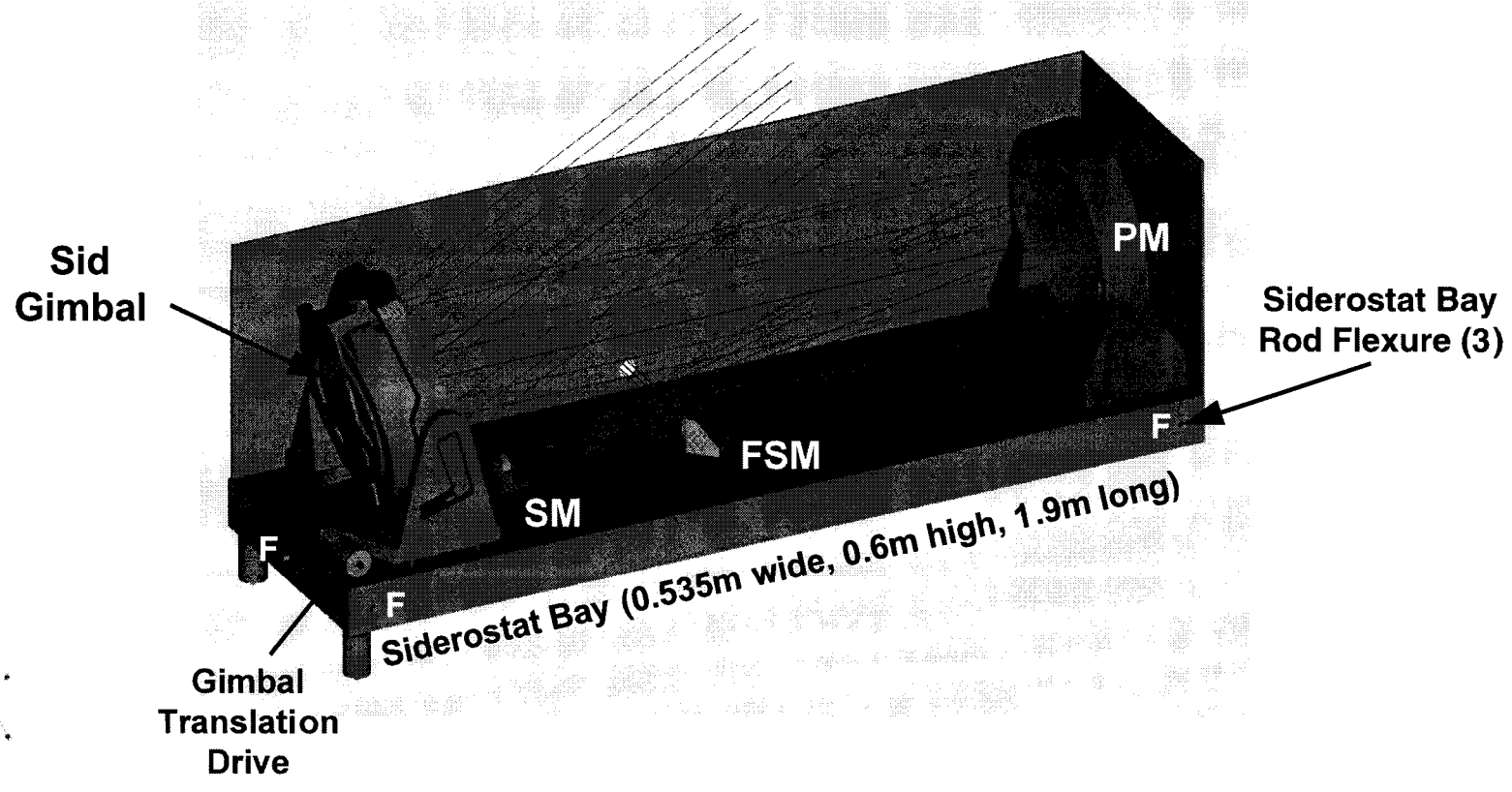
Siderostat Bay Layout



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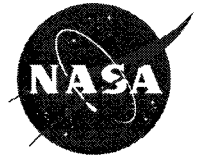

Development of the SIM science program

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- Bahcall Report (NAS, 1991) *"The Decade of Discovery"* recommended an astrometric mission with an accuracy of 3 - 30 μas
  - Search for planets around stars within 150 pc
  - Distances to stars throughout the Galaxy
  - Demonstrate technology for future interferometry missions
- Space Interferometry Science Working Group report (1996)
- SIM Science Working Group
  - Team of ~20 scientists with astronomy / technology interests
  - Develop Science Requirements and advise NASA

SIM astrometric performance summary

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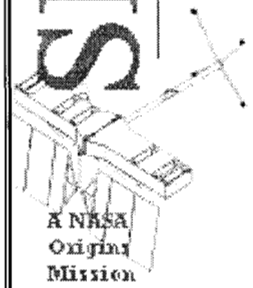
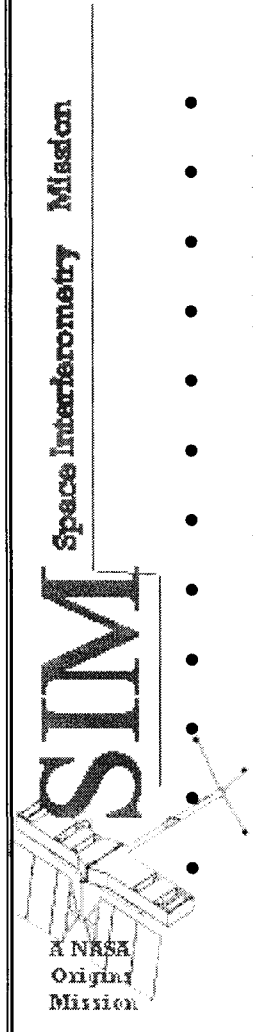


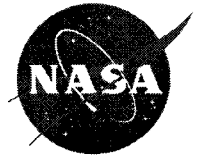
- **Observational Band**: 400 - 1000 nm
- **Global (all-sky) astrometry**
  - Astrometric accuracy: 4 μas (end of mission)
  - Faintest stars: V = 20 mag
    - brightness of a solar-type star at 10 kpc
  - Yields distances to 10% accuracy, anywhere in our Galaxy
- Proper motion accuracy: 2 μas / yr
  - Motion due to parallax at 10 pc is detectable in a few minutes!

- **Local (narrow-angle) astrometry**
  - Measurements are made relative to reference stars (within ~1°)
  - Astrometric accuracy: 1 μas in one hour
    - This angle subtends a length of 1,500 km at 10 pc distance !
    - Detect proper motion of Barnard's star in 3s !

SIM science summary

- Search for astrometric signature of planets around nearby stars
- Distances to spiral galaxies using rotational parallaxes
- Mass distribution in the halo of our Galaxy
- Dynamics of our Local Group of galaxies
- Spiral structure of our Galaxy
- Calibration of the cosmic distance 'ladder'
- Ages of globular clusters
- Internal dynamics of globular clusters
- Masses and distances to MACHOs
- Accurate masses for low-mass stars in binaries
- Imaging of emission-line gas around black holes in active galactic nuclei
- Imaging of dust disks around nearby stars (nulling)





Scheduling SIM

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- SIM is a versatile *pointed* instrument
  - High astrometric accuracy at faint limiting magnitudes (but smaller total number of targets)
    - Galactic halo
    - Tidal tails from interactions
- Enhanced accuracy in relative (narrow-angle) mode
    - Planet detection
    - Rotational parallaxes
    - Internal dynamics of star clusters
- Flexible scheduling
    - For targets of opportunity, e.g. MACHO events, supernovae …
    - For changes in science priority
      - Search for additional planets in known planetary systems

Observing Astrometric Grid Stars - 'Tiling' the Sky

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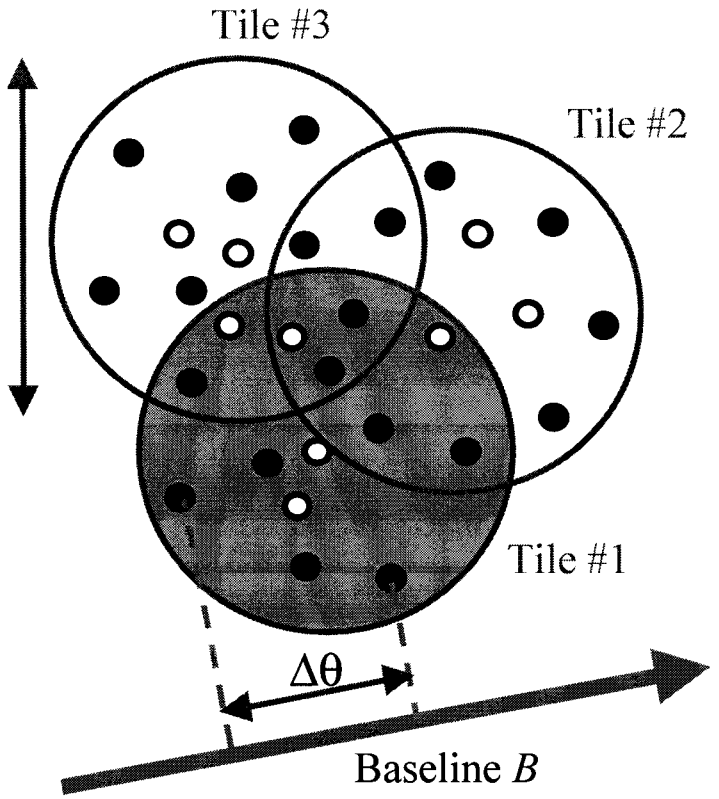
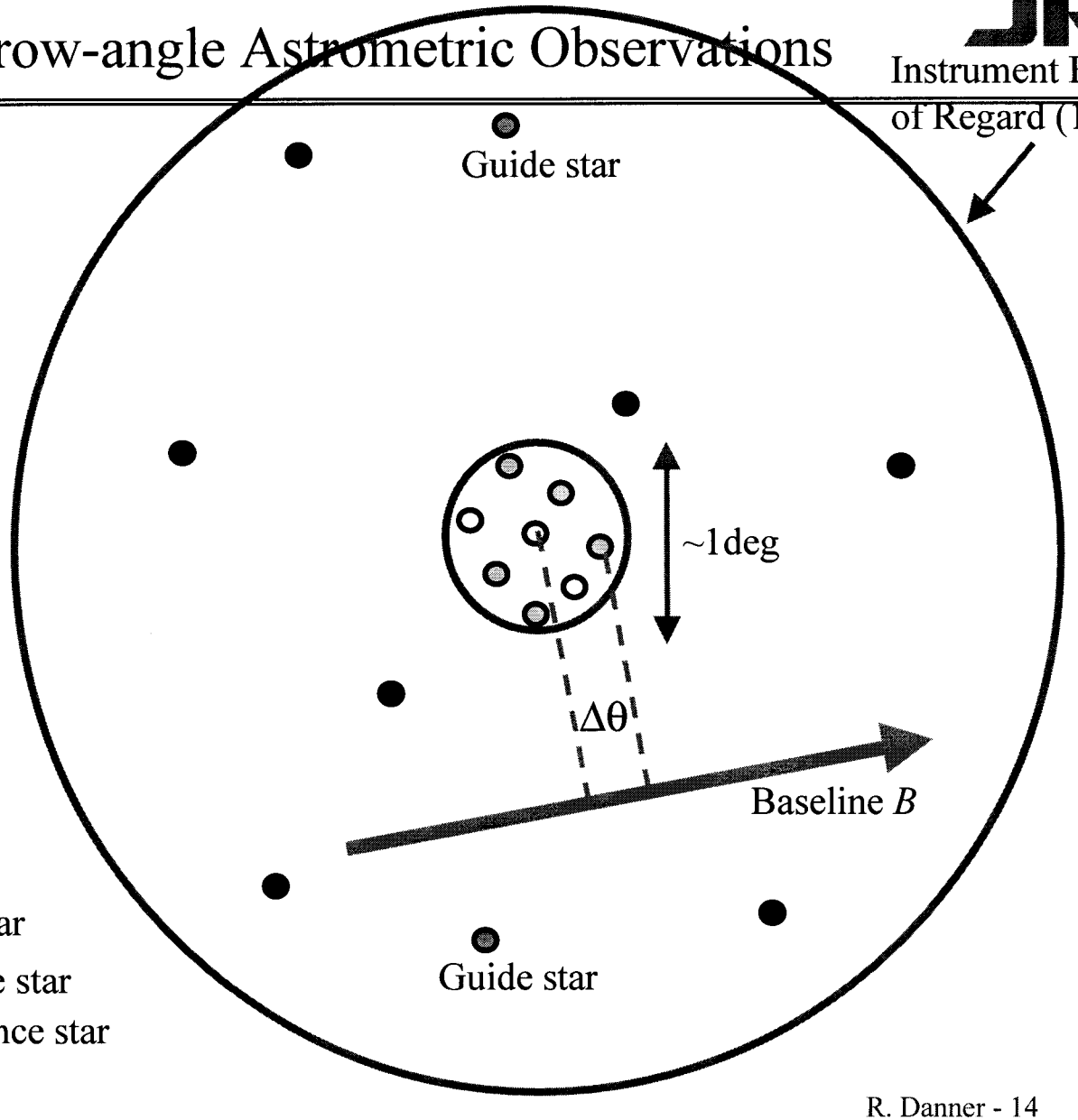
Instrument Field of Regard (15deg)

● Grid star
○ Science star



Narrow-angle Astrometric Observations

Narrow-angle performance = 1 μas in 1 hour



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Narrow-Angle Astrometry

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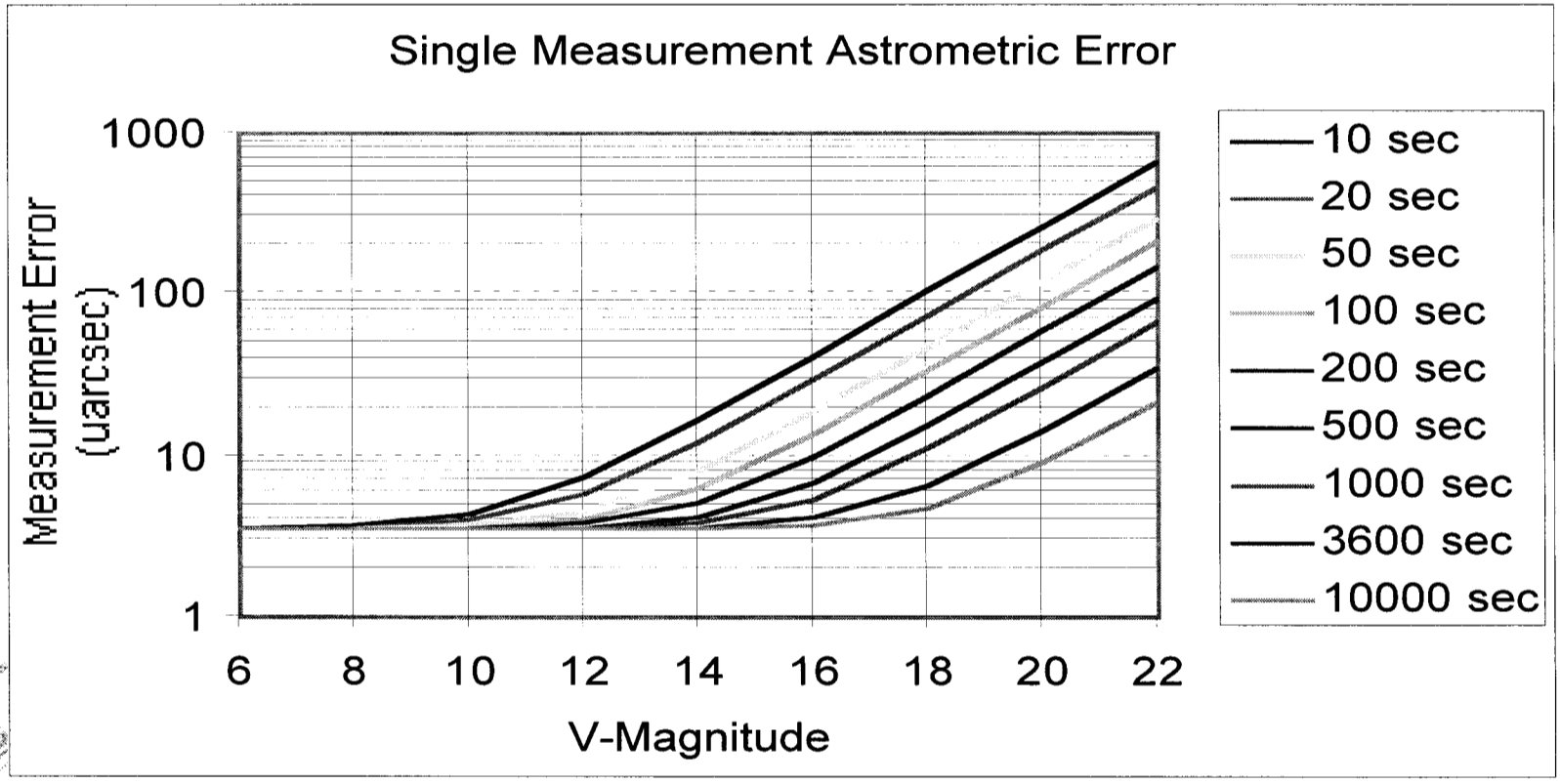

Astrometric Parameter Space

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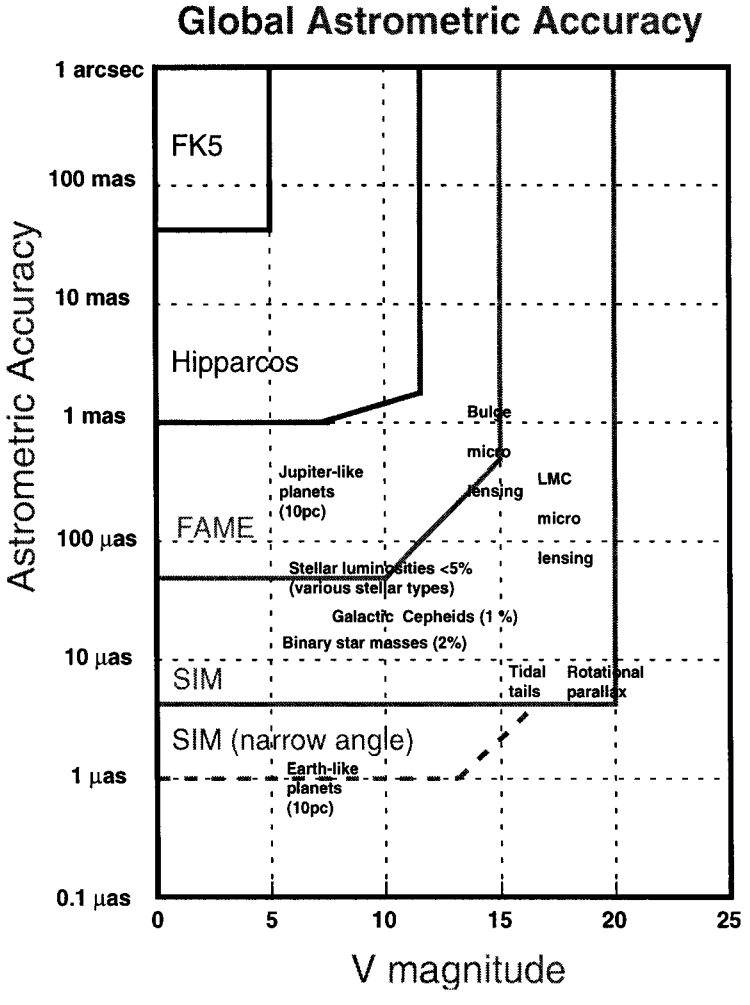
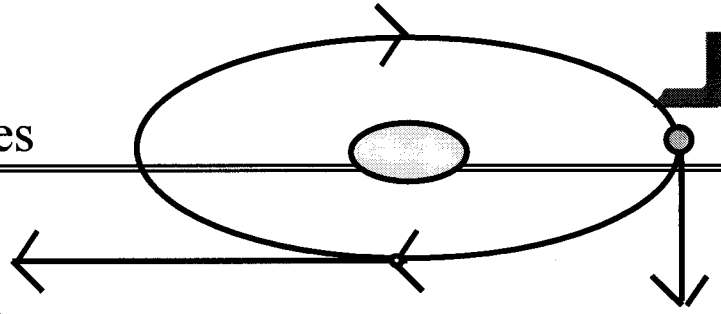
- SIM will reach V = 20 and 4 μas accuracy
- Enables demanding programs such as rotational parallaxes and tidal tails of disrupted dwarf galaxies



Measuring distances to spiral galaxies using rotational parallaxes



Transverse velocity = $V_{rot} = \mu_{rot} D$

Radial velocity = $V_{rot} \sin i$
Transverse velocity = $V_{rot} \cos i$

- Measure distance to a galaxy in units of meters
  - 'Single-step' measurement
  - Calibration of **Tully-Fisher relation** (luminosity vs. peak rotational velocity)
    - Hence accurate distances for very distant galaxies
  - Accuracy ~5 % for disk galaxies out to ~ 5 Mpc
- Method: Astrometric measurement of galactic rotation
  - Example: M31 at 770 kpc. Rotational velocity (almost flat rotation curve) V_{rot} = 250 km/s $\Rightarrow$ 40 μas/yr
  - Select ~25 A-F supergiant stars along major and minor axes
  - Measure proper motions (μ_{rot}) using SIM - narrow-angle mode
  - spectroscopic radial velocities
  - Solve for distance from ratio of measurements of μ_{rot} and V_{rot}

Space Interferometry Mission

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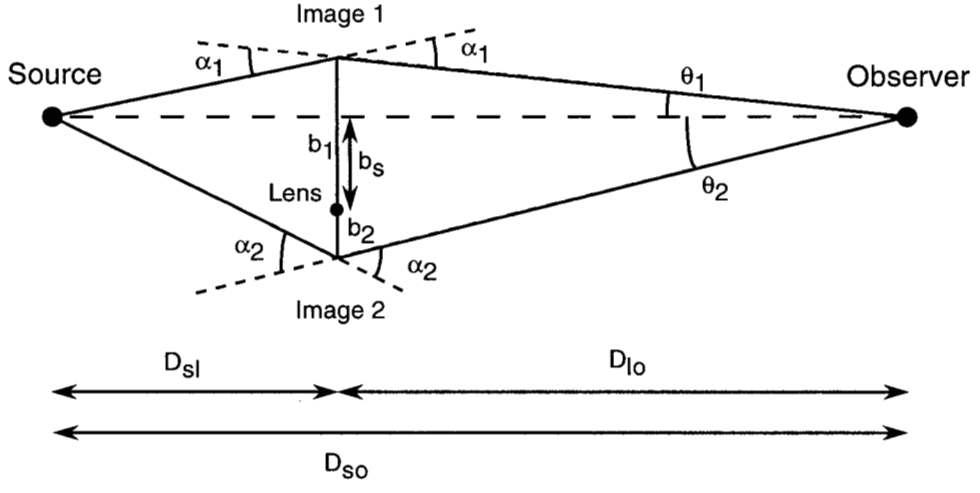
Using MACHOs to probe dark matter



- SIM observes the bending of light by dark matter ('MACHOs') due to chance alignments
- What are the masses, distances and kinematics of MAssive Compact Halo Objects?
- Lensing candidates provided by ground-based monitoring of brightness of many stars
  - Scheduled on SIM as targets of opportunity

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Dynamics of open star clusters

- Internal dynamics of open star clusters (e.g. Pleiades)
  - Not restricted only to the closest clusters
- 3-D motions of a large sample of stars
  - trace mass distribution of the cluster -> total mass
  - 3-D orbits provide info on formation history and evolution
  - Cluster rotation?
  - Distribution of binary stars
  - Mass segregation

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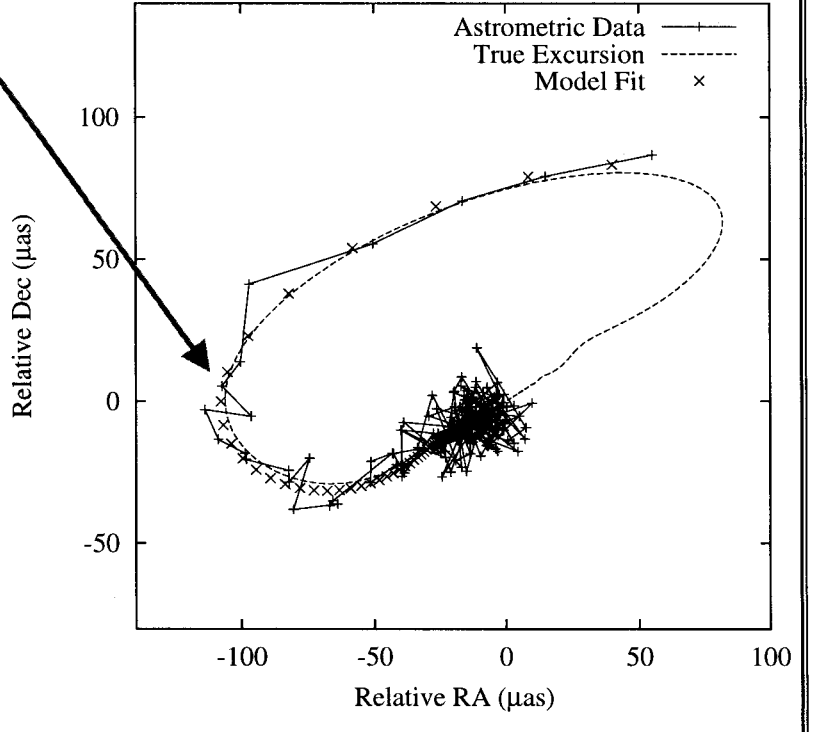
Using MACHOs to probe dark matter (cont.)

- Apparent star position moves in a characteristic pattern with relatively large amplitude of ~100 μas
- Symmetry of track broken by Earth orbit motion: lens parallax
- Derive : mass, distance, and velocity of the lensing object
- Possible SIM observational program (following ground-based photometric survey detection):
  - >~50 LMC, SMC, and bulge sources
  - Astrometric accuracy 5-25 μas (corresponding mass error of 5-35%)



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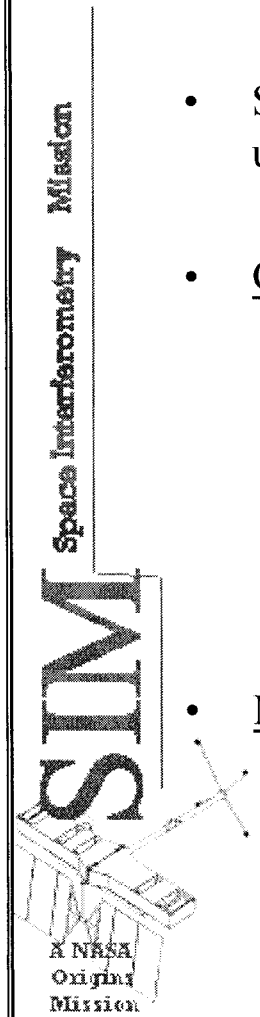
Galactic Dynamics

- Study the 'classical' problems of size, mass distribution, and dynamics of the Galaxy, using stellar velocities

- Questions include:
  - Vertical mass distribution of the Galactic disk, near the sun
  - Kinematics of the outer disk of the Galaxy (beyond R_o)
  - Kinematics of K giant stars in the outer halo - mass distribution
  - Understanding the central bar of the Galaxy
  - Debris tail orbits (Sagittarius dwarf galaxy) - phase space signature

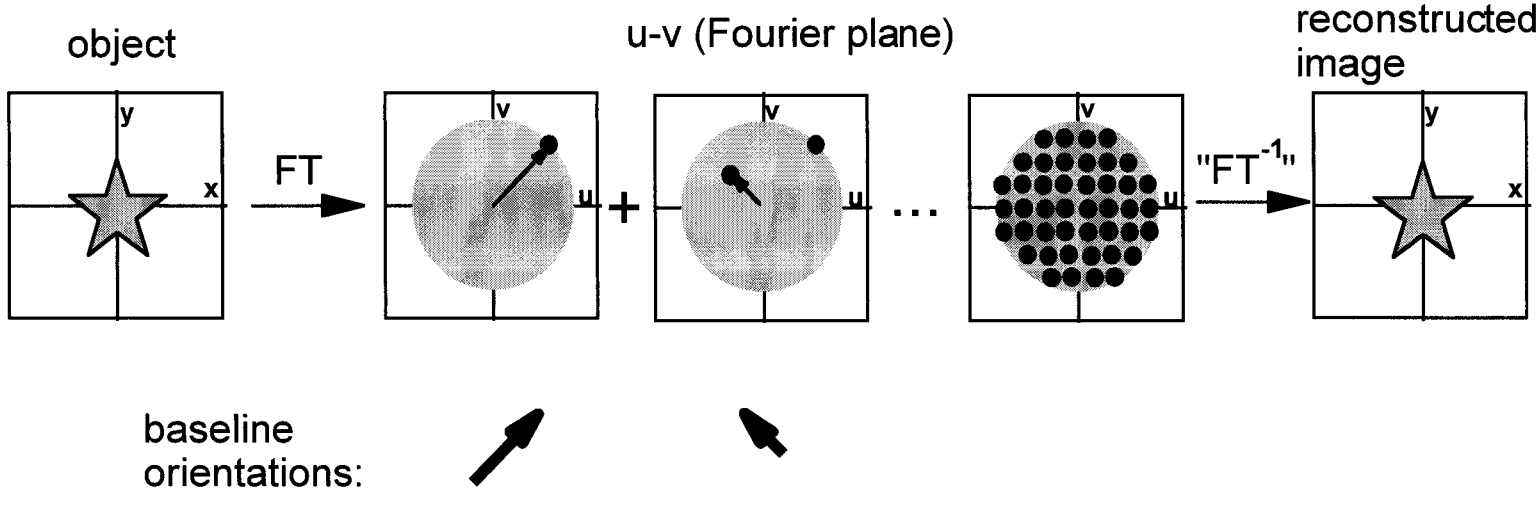
- Method: derive 6-D phase-space coordinates for selected samples of stars:
  - Distances to 5% at 10 kpc, for stars with V < 20
  - Proper motions to 0.1 km/s at 10 kpc
  - Combine with ground-based radial velocities



Astrophysics of stars in our galaxy

- Astrometric measurement of orbits of low-mass binary stars
  - Goal is to measure stellar masses to < 1 %
- *M* vs. *L* relation is poorly known at the low end of main sequence ($1.0 > M > 0.08\ M_o$)
  - Measure parallax distance and orbital elements from astrometry
  - Combine with ground-based (spectroscopic) radial velocities
  - Test models of stellar structure
  - Implications for mass distribution in the Galaxy
- Stellar evolution
  - Certain stellar classes are rare in solar neighborhood:
    Cepheids, OB (main sequence) stars
  - Parallax distances to Cepheids to 1 %
    Test models of Cepheid pulsation; zero-point for *P-L* relation
  - Calibrate OB star luminosities --> accurate placement on the H-R diagram
- Astrometric search for low-mass companions (brown dwarfs, etc.)

Imaging with an Interferometer



- The interferometer measures the Fourier transform of the object
- Each baseline orientation selects one point in the (u,v) plane
  - The data for this point is the fringe visibility and phase
- With many baseline orientations, you fill in the (u,v) plane
- The image is reconstructed from these Fourier-domain measurements

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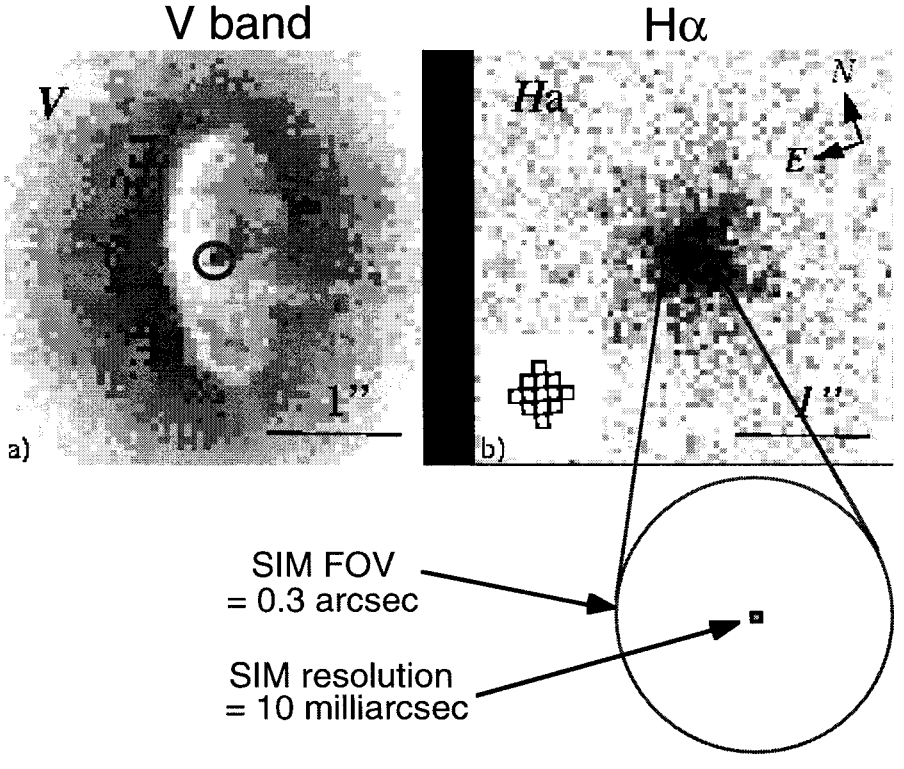
Massive black holes in active galactic nuclei
Example: NGC 4261

- HST / WFPC2 V-band and Hα images show an inclined dust disk surrounding a bright emission-line region region centered on the nucleus
- HST / FOS spectra indicate nucleus contains a black hole with mass ~ 1.2 x 10^9 M_o
- Hα image barely resolved at 0.12 arcsec
- SIM can image the central 0.3 arcsec at 10 milliarcsecond resolution using low-resolution spectroscopy
- SIM will probe the gas dynamics closer to the black hole

HST/WFPC2 images of nucleus of NGC4261, at a distance of 30 Mpc (Ferrarese et al. 1996)



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Searching for planets around other stars

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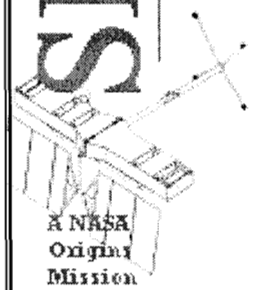

- Questions:
  - Are planets around other stars common?
  - Earth-like planets ??
  - Are certain spectral types favored?
  - What is the mass and orbit distribution of planets?

- Method: astrometric detection of 'wobble' due to gravitational tug of unseen planets
  - Complements radial velocity method
    - RV more sensitive to shorter periods
    - Astrometry more sensitive to longer periods

Planet Detection - Search Regimes for SIM

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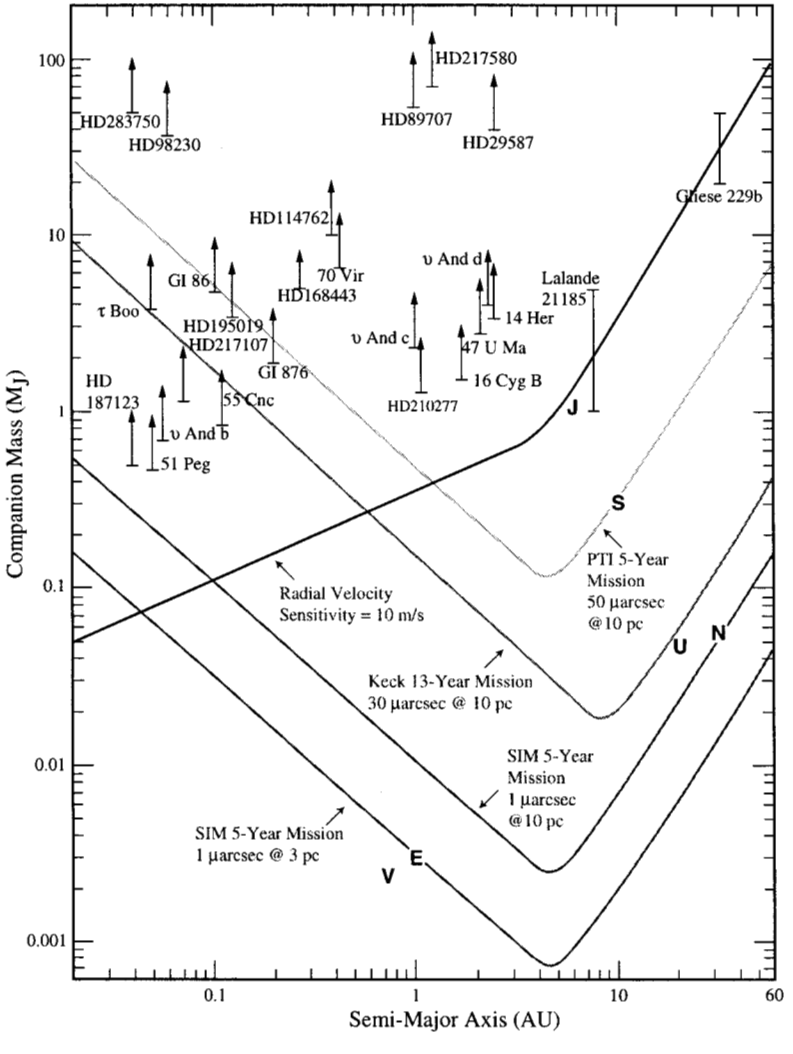
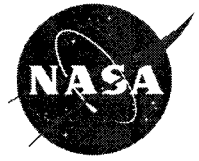
- Jupiter-mass planets
  - Signature is ± 5 μas at 1 kpc
  - Very large number of available targets
- Intermediate mass range: 2 - 20 Earth masses
  - Massive terrestrial planets
  - Detectable to many 10s of pc
  - SIM can survey a large number of stars for planets less massive than Jupiter
- Earth-like planets
  - The most challenging science for SIM
  - 1 Earth mass at 1 AU -> ± 0.3 μas signature at 10 pc
  - Earths detectable only out to a few pc
  - Orbit parameters only for the closest systems





Observational Clues to Planet Formation

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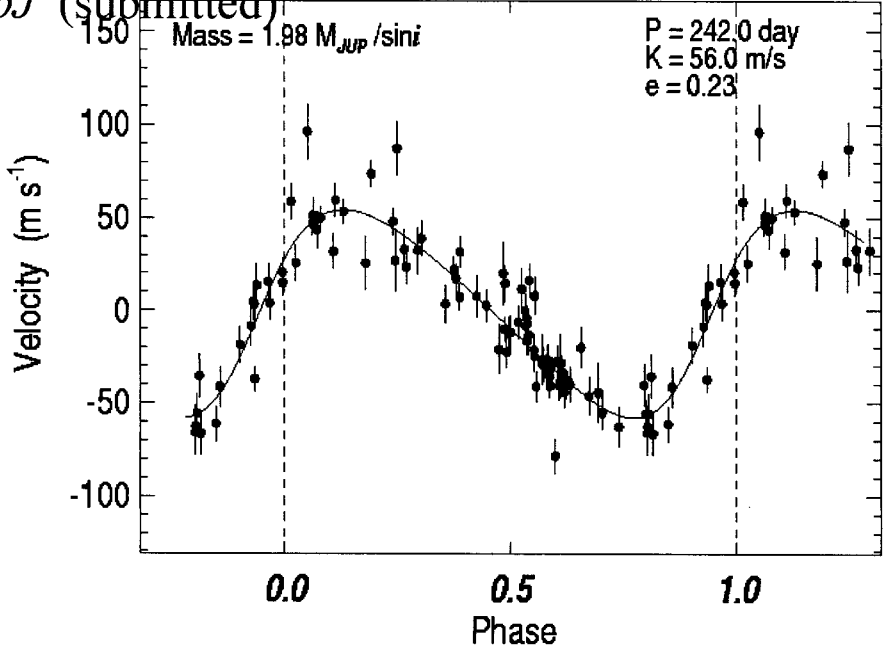
- Massive terrestrial planets: 2 - 20 Earth masses
  - Planets in this mass range may be indicative of the formation process in a protoplanetary disk
    - If disk gas dissipates rapidly, one might expect to find 2-20 Earth-mass planets, but no Jupiter-mass gas giants
- Sub-stellar companions: mass determination
  - May expect a *lower* mass cutoff to brown dwarf masses, associated with fragmentation in protostellar clouds
  - May expect an *upper* mass cutoff to planet masses, depending on protoplanetary disk density
- SIM will address both of these mass regimes
  - SIM is sensitive to 2 - 20 Earth mass planets, not detectable by other methods
  - SIM can measure planet masses unambiguously, from astrometric orbit and parallax

Properties of Upsilon Andromedae System

- Stellar type F8V
- Mass = 1.3 solar mass
- Distance = 13.5 pc
- Planetary companions:
  - b: $M = 0.72\ M_{jup} / \sin i$, a = 0.06 AU, P = 4.6 days, e = 0.04
  - c: $M = 1.98\ M_{jup} / \sin i$, a = 0.83 AU, P = 242 days, e = 0.23
  - d: $M = 4.11\ M_{jup} / \sin i$, a = 2.50 AU, P = 1269 days, e = 0.36
- Ref: Butler, *et al.* 1999, *ApJ* (submitted)

- Radial velocities
- Fit to 'c' companion only
- (b and d fit subtracted)



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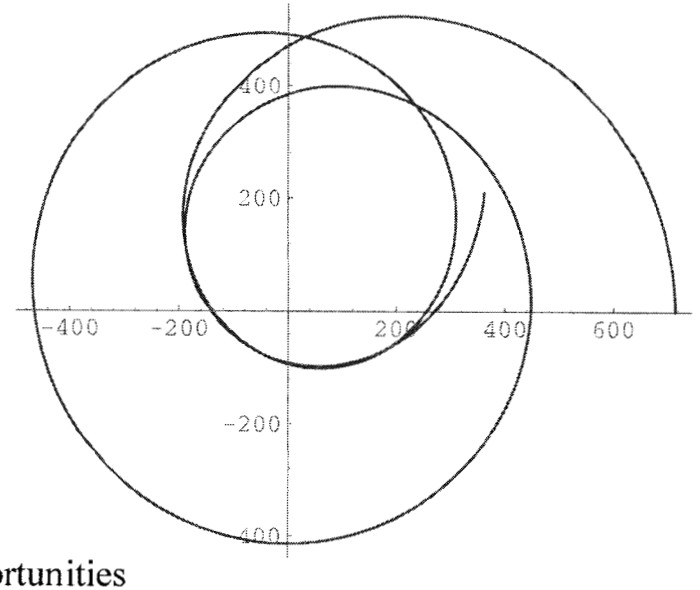
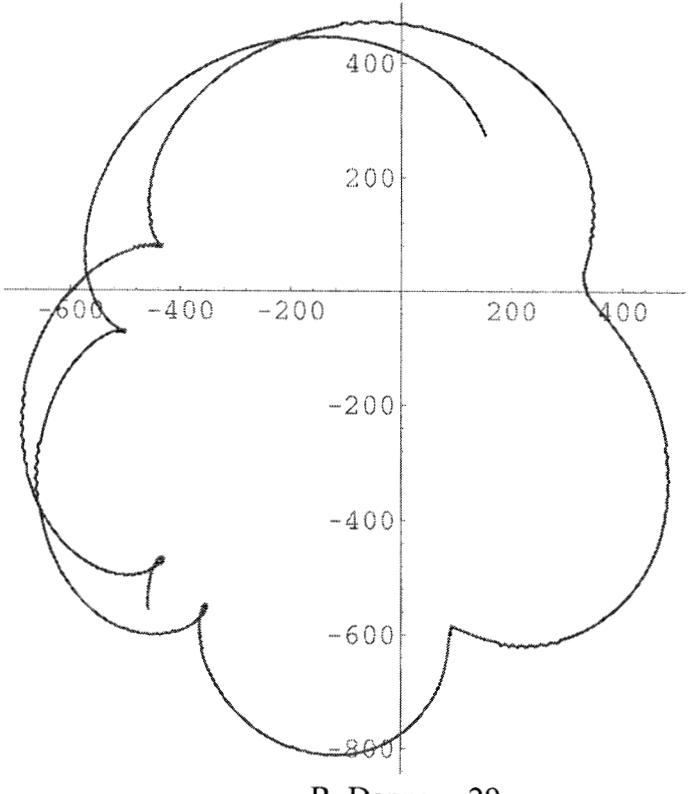
Astrometric Detection of Upsilon Andromedae

- SIM accuracy = 1 μas, single measurement
- Astrometric signatures
  - b: amplitude = 2.3 / sin *i* μas
  - c: amplitude = 89.3 / sin *i* μas
  - d: amplitude = 557.5 / sin *i* μas

Solar system
viewed from 15 pc, *i* = 0 deg
35 years



Ups Andromedae
Minimum signature: *i* = 90 deg
viewed face on, *i* = 0 deg
5 years



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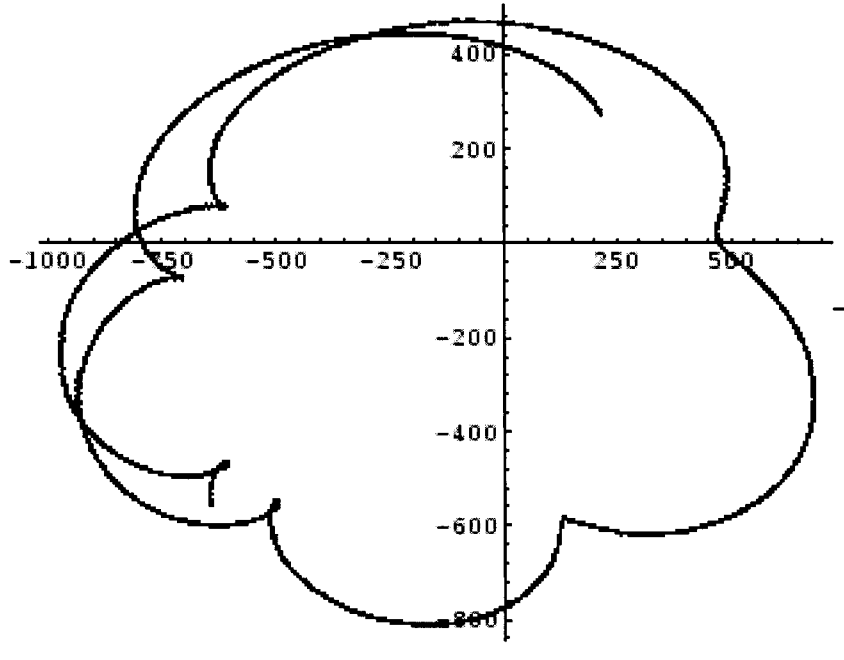
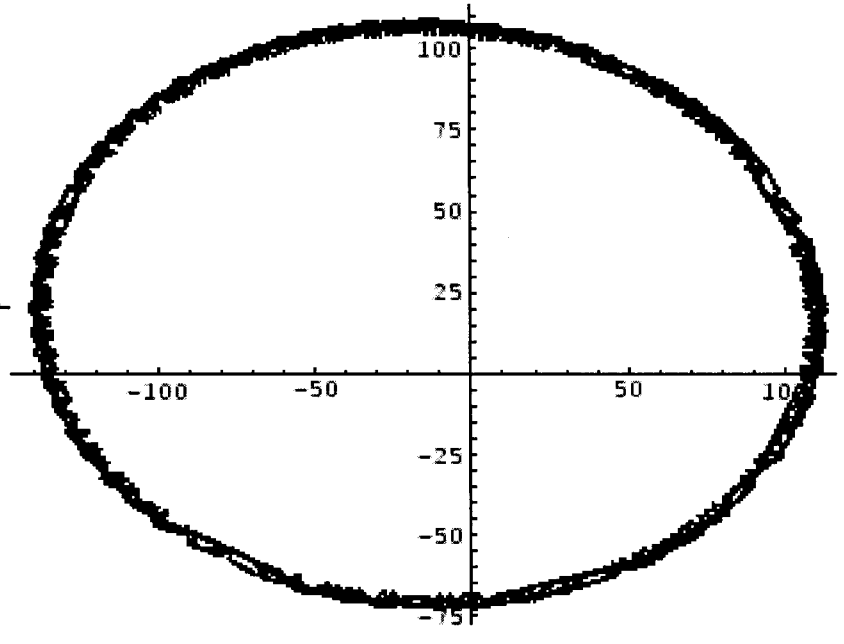
Astrometric Detection of Upsilon Andromedae

- Orbital inclination i = 45 deg
  - Assumed same for each planet
- Astrometric signature increases by 1.41
- 5 years



- Planets b and c only
- i = 45 deg
- 3 years



Planet Detection - Further Questions

- SIM will begin to answer (some!) of these questions, especially for systems with Jupiter-mass planets
  - How common are planets around other stars?
  - Are certain spectral types favored?
  - What is the mass distribution of planets?
  - What is the orbit radius (and eccentricity) distribution?
  - Are multiple systems common?
  - Are multiple systems co-planar? Are they stable?
  - What is the Galactic distribution of planetary systems?
- For multiple-planet systems, astrometry is *essential* for orbit characterization
  - Radial velocity studies do not measure inclination, or PA on the sky
- Complete answers will require statistical study of a very large sample, at very high sensitivity
  - Key science objective for GAIA

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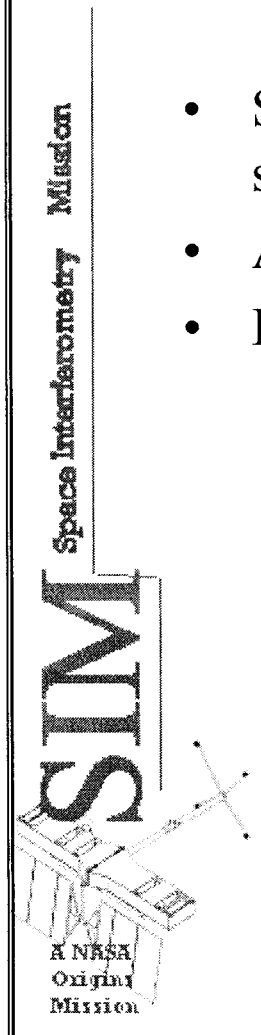
Toward Future Missions

- SIM will serve as a technology precursor for future interferometers in space
- A direct precursor to the Terrestrial Planet Finder
- Demonstrate:
  - Operation of a Michelson interferometer in space
  - Fringe nulling
  - Control of thermal and vibration environment
  - Synthesis imaging in space
  - Precision deployments
  - Angle and pathlength control



Key SIM Technologies

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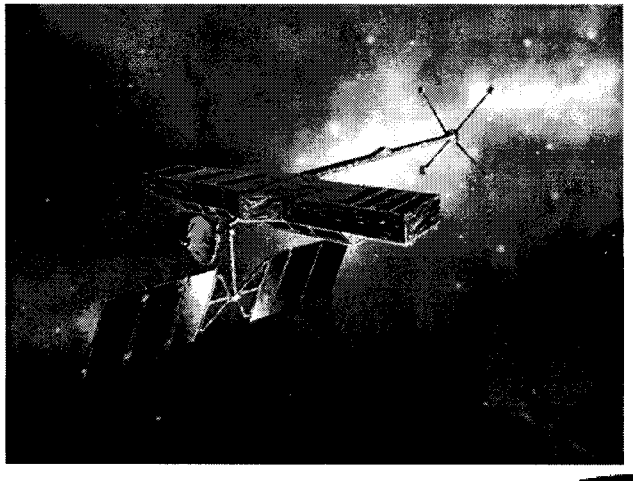
Thermally-Stable Optics
Milli-Kelvin Thermal Stability

Quiet Structures
Micron Stability

Metrology
Sub-Nanometer Relative Knowledge

Active Optics
Nanometer Control



Starlight Fringe Detection
Sub-Nanometer Fringe Tracking

Starlight Nulling
Focal Plane Nulling: (10^{-4})

Interferometer Modeling
Integrated Optical, Mechanical, Thermal & Control

Interferometer I&T

Picometer Laser Gauge
- one of the key component building block

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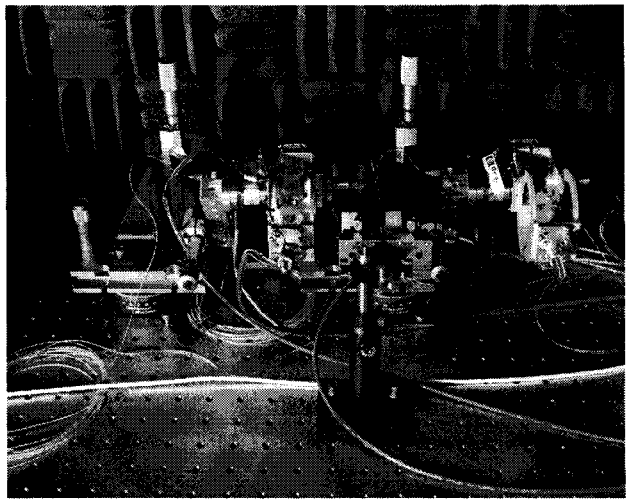
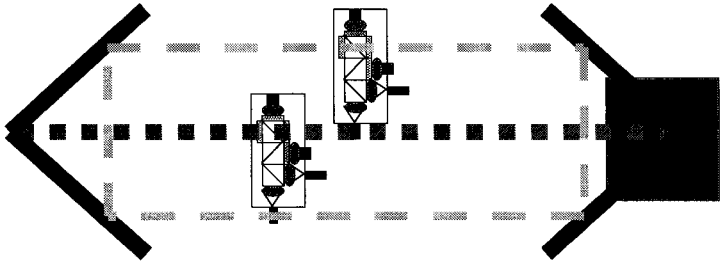
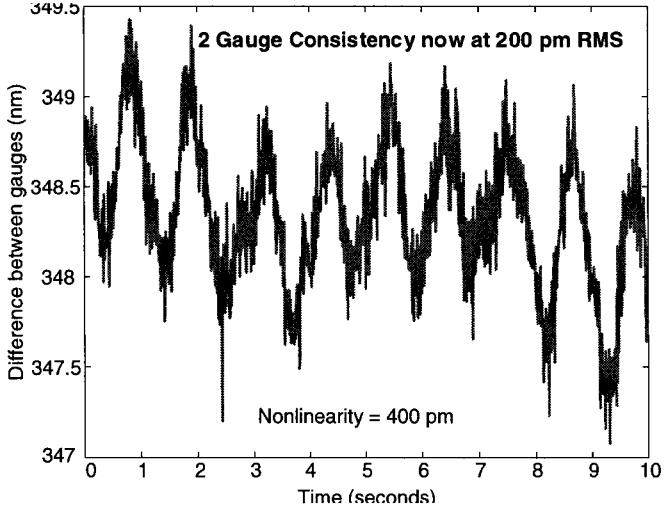


Heterodyne Metrology Gauge

- SIM will use 10's of these gauges to monitor relative motion of optics
- Gauge precision maps directly to science precsion: 30 pm <=> 1 uas
- Recently demonstrated 200 pm gauge consistency in the "2-Gauge" experiment -- targeting another order of magnitude



"2-Gauge" Experiment



Kite Experiment
-- building laser gauges into metrology trusses

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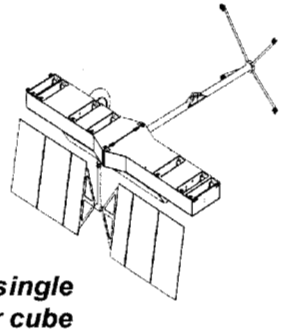
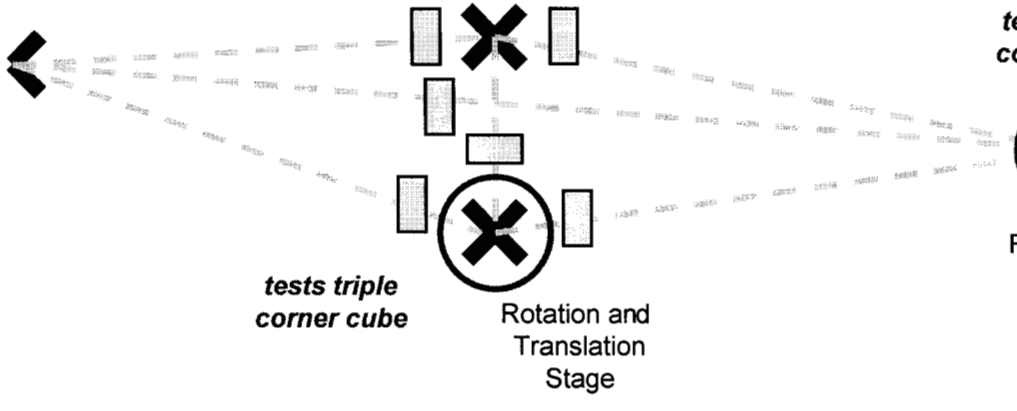
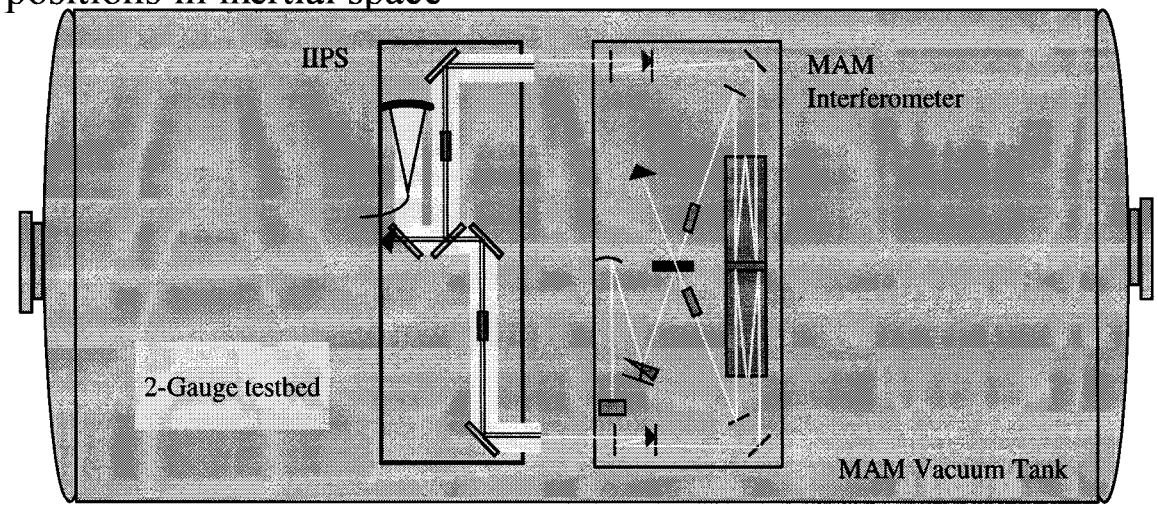
- SIM external metrology system is a large scale metrology "truss"
- Kite demonstrates a picometer metrology truss in two dimensions
  - Use redundant metrology truss to measure the errors due to corner cube motions (rotations and translations)
    - corner cube surface imperfections
    - polarization effects





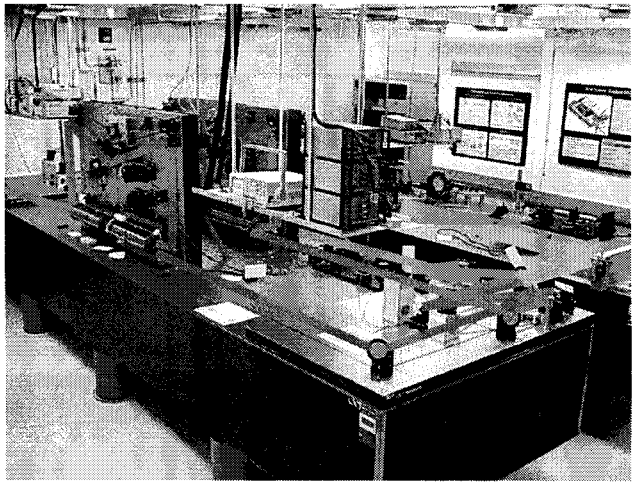
MAM-1 and MAM-3 System Testbeds

- SIM has three baselines (one science and two guides) that function as individual interferometers, and together to transfer guide star position knowledge to locate science stars
  - MAM-1 is a one-baseline testbed that demonstrates that metrology and starlight sensing can be integrated and provide consistent outputs at the picometer level
  - MAM-3 is a three baseline testbed that demonstrates the transfer of guide star position knowledge with the precision required to measure science star positions in inertial space

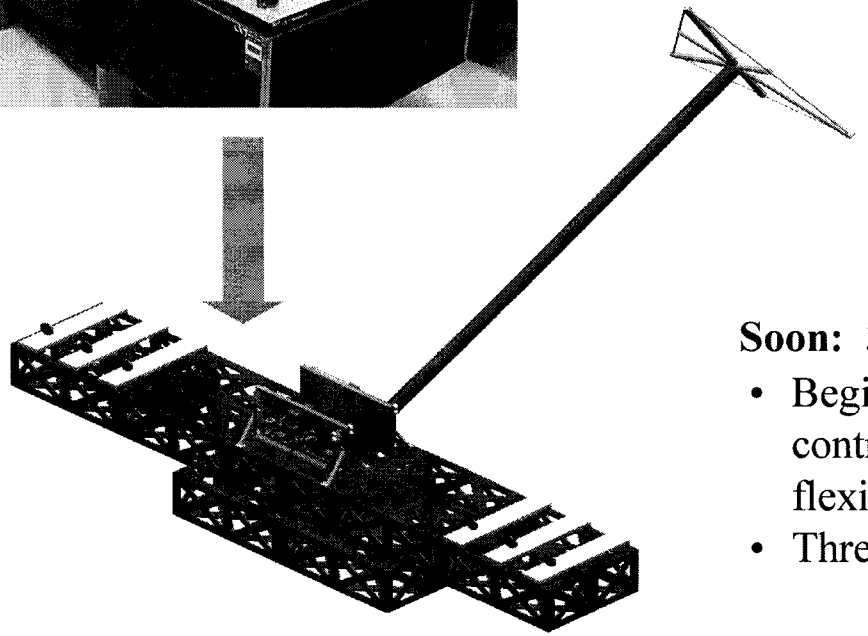


MAM-1 schematic

SIM System Testbed (STB-3)
- nanometer control at full scale, full complexity



- Completed assembly of all three baselines -- 3 baseline functionality expected very soon
- Completed detailed design of SIM-scale flexible structure to be built and installed by end-2000



Soon: 3 baselines on structure

- Begin nanometer active control experiments on flexible structure
- Three baselines, full scale

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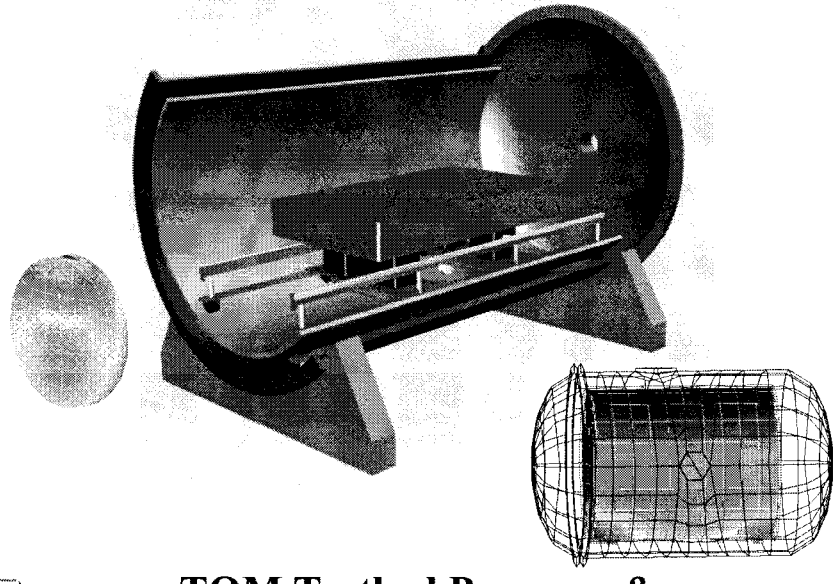
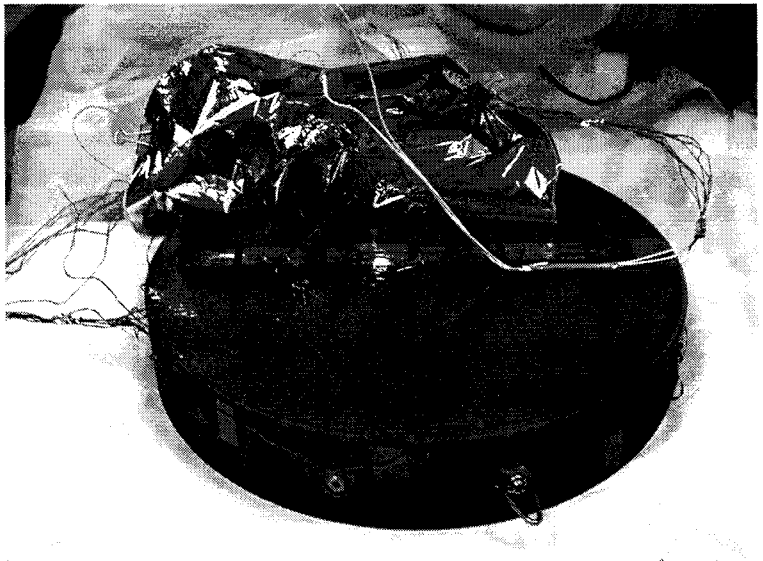
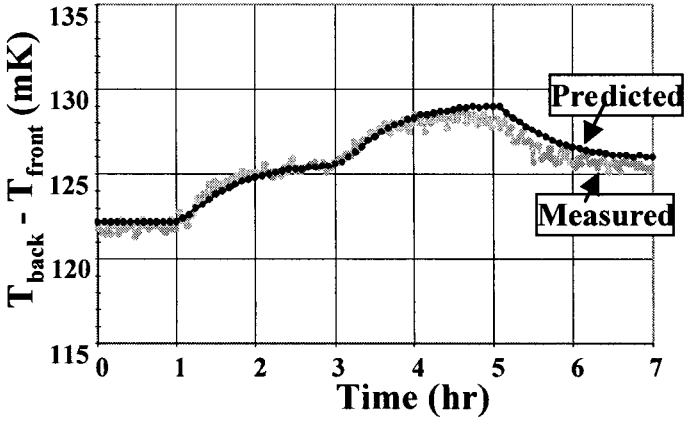
Thermal Optomechanical (TOM) Testbed
- *mK thermal control means pm deformations*



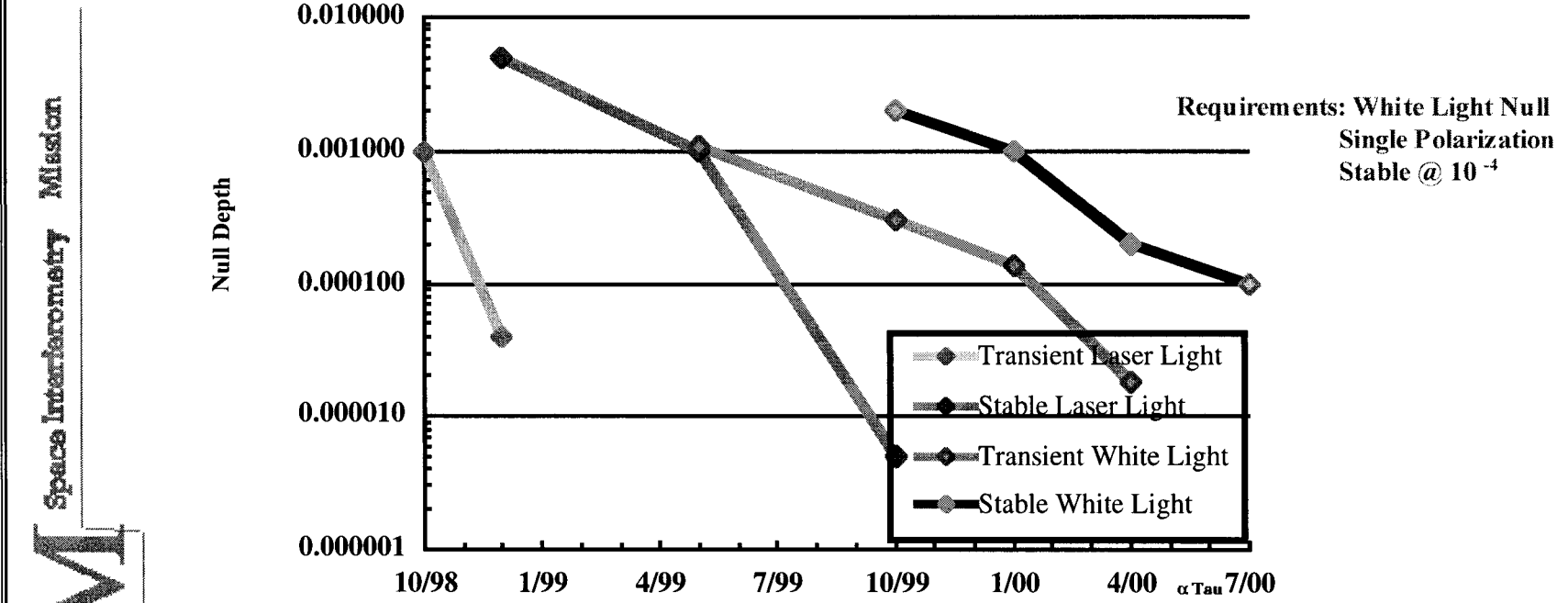


TOM Testbed Progress & Plan

- Demonstrated ability to accurately model temperature gradient changes on SIM-scale optics (33 cm) -- predictions good to about 20% in the mK regime
- Next step -- correlate mK temperature changes with pm mirror figure changes



Starlight Nulling Progress



Requirements: White Light Null
Single Polarization
Stable @ 10^{-4}

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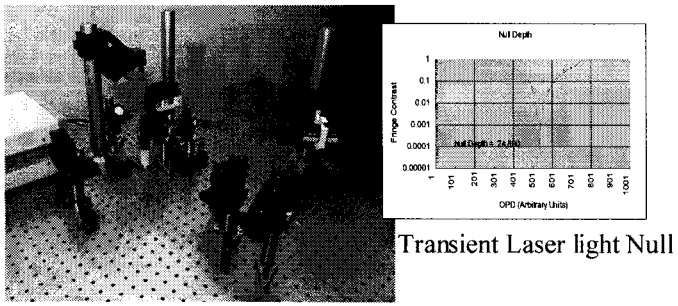
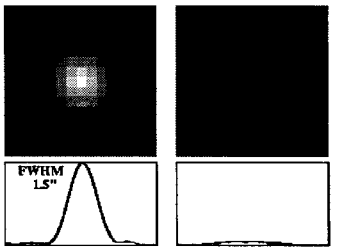


Transient Laser light Null



constructive destructive

UofA results from MMT
20:1 at 10 μm